<u>ANSWER TO REFEREE 1:</u>

Referee #1

Overall comment

In this revised manuscript, the authors have addressed all my comments in a satisfactory way. To my mind, the paper is now clear and reaches substantial conclusions of interest for the scientific community. I therefore recommend the paper for publication, provided the few technical corrections given below are made.

Copyediting and typesetting

– p. 1, l. 27: high-apogee
– p. 4, l. 1: whether the trapping boundary
– p. 8, l. 11: as separate measures
– p. 10, l. 9: so the increasing of --> so an increase in
– p. 11, l. 2: Investigacin --> Investigación; Tecnologa --> Tecnología

Dear reviewer 1!

Thank you very much for careful reading of our paper and for all corrections!
We have made all necessary corrections in the text.

<u>ANSWER TO REFEREE 2:</u>

Referee #3

Dear Editor,

This is my review of the paper « Relative locations of the polar boundary of the outer electron radiation belt and the equatorial boundary of the auroral oval » by M. O. Riazanteseva et al. submitted to AnGeo.

This article addresses the problem of finding the position of the polar boundary of the outer electron radiation belt (ORB), relative to the position of the auroral oval (AO). The authors perform a statistical study using the data of the METEOR-M No1 auroral satellite for the period from 11 November 2009 to 27 March 2010. From it they deliver the respective position of the two structures.

I am the third reviewer of this article and I do recommend publications based on the following comments (A) and once the few additional changes I am asking (B) below are made.

A) As a third reviewer, I can see how this article has been improved since its submission. I agree with Reviewer 2 that this article provides a useful scientific step forward (now that some modifications have been made. Reviewer 1 asked to go a bit further in the analysis by trying to determine why d(lat) changes with increasing geomagnetic activity (from totally quiet to moderate activity). This has been done
by the authors through Figure 4 and 5. Figure 4 showing the penetration of the ORB into the AO in terms of delta_Latitude is important. Reviewer 2 asked « new figure(s) that would provide clarity for the reader and confirm that the algorithm is producing results that are consistent with the previous work cited in paragraph 1&2, section 1 ». This has been done; figure 6 showing the distributions of the position of equatorial boundary of the auroral oval (green bins) and the polar ORB boundary (red bins) from the L different AE index is important. The authors have therefore accounted for the changes asked by both reviewers and their final figures are 1- clear to me, 2- bringing a statistical description for different geomagnetic activities, 3- support well the conclusions of the article.

B) There were issues on the energy range for the determination of the ORB and AO. In my review below, I come back on the energy dependence that is a key point to discuss. The main modification I am asking should be fast to do as I only ask 1- to include a small discussion on the energy-dependence of the ORB (with a link to SAPS), 2- to account for recent publications.

My intension is to recommend publication in AnGeo and to see this article published within short delays.

Dear Reviewer 3!

We are grateful to the reviewer for the attention he/she raid to our paper and for a very useful discussion. Unfortunately, the study of the nature of the outer radiation belt and its formation is not the main task of the Meteor satellite mission. Also we have no measurements of electric fields necessary for the analysis of the formation of the ORB. Therefore, it is impossible to add something else, which could be used for the study of the ORB dynamics in addition to the results shown here: the overlapping of the auroral oval and the ORB. We hope that this result is important, and there were very little studies on this subject despite the results of Akasofu [1968].

We have tried to analyze all papers relative to this subject and did not find any comparison of the position of the auroral oval with respect to the ORB, made using the data from a single satellite. The observed overlapping of the ORB with the auroral oval raise the question of the auroral oval mapping considering the fact that the drift trajectories of the energetic electrons should be closed around the Earth, and hence cannot be located in the plasma sheet. This result indeed agrees with the latest results (see Antonova et al. [2017, doi:10.1016/j.jastp.2017.10.013] and references in this paper). It became clear that the main part of the auroral oval is mapped to the outer part of the ring current. Such mapping was obtained using a morphological method which does not involve any existing geomagnetic field model, most of which are very overstretched (see [Peredo et al., 1993, JGR, v. 98, No 9., P.

15,343-15,354, doi:10.1029/93JA01150; Reeves et al., 1996, Geophys. Mon. 97, p. 167-172, doi:10.1029/GM097p0167 ; Weiss et al. , 1997, JGR.,102, 4911–4918, doi:10.1029/96JA02876; McCollough et al., 2008, Space Weather,6(10), doi:10.1029/2008SW000391; ets.]). These new results about the auroral oval mapping made it necessary to re-analyze the relative position of the trapping boundary of energetic electrons with respect to the auroral oval, which was done in our current paper. The results obtained in our study helped us to understand why the previous statistical studies about a relative location of the outer ORB boundary and the equatorial boundary of the auroral oval did not give an unambiguous picture and was interpreted as a coincidence of both boundaries Feldstein and Starkov [1970, PLANET SPACE SCI, 18, 501–508, doi:10.1016/0032-0633(70)90127-3, 1970]).

Main corrections:

1-: On the energy-dependence

Although authors focus on the polar boundary of the outer belt, I ask here the question of the impact of energy dependence of the outer belt on its shape, and, therefore, on its boundaries. The inner boundary of the outer belt is extremely energy dependent as shown very recently (e.g. Reeves et al. 2016; Ripoll et al. JGR 2017 and references in them) from the Van Allen Probes, from L~4 to 6. As L-increases above L~6 reaching now the polar boundary of the outer belts, in which the authors are working on, some of this energy-dependence will be kept, in particular for quiet times, for which the plasmasphere extends up to there. From Figure 6 of the authors, it is interesting to see that the probability is higher in the Southern hemisphere. (As a comment, the position of the plasmasphere is determinant on the energy-dependence of the ORB structure, but not only, as wave-particle interactions (WPI) from Chorus waves outside of the plasmasphere will also print an energy-dependence structure of the outer belt). What is interesting about quiet times, on which the authors focus on (but not only), is the great stability of the outer belt. For instance Ripoll et al. 2014 analyzing HEO data shown months of stability of the outer belt for E>100 keV, reinforcing the relevance of defining outer belt boundaries and positioning them onto known structures (aurora oval, ring plasma or current, plasma sheet, etc.). Still, the stability degrades as L-shell increases above 5-6. (As a comment, there the drift trajectories of the energetic electrons must be closed around the Earth must be more recent observations from the Van Allen Probes, which we let the authors find themselves). During active times, because WPI are extremely energy-dependent, it is likely that the energy-dependence will also show up one way or the other, to print the whole outer belt structure.

Since the discovery of the outer radiation belt by Vernov and his colleagues in 1957 using the data from the second satellite (see the discussion of Baker and Panasyuk [2017, Physics Today, 70(12), 46-51, doi: 10.1063/PT.3.3791]), the dynamics of the ORB was analyzed in many works, including the problem of its stability, and the energy dependence (see figure below from the AE8 model). The AE8 model was developed using the data of high orbiting satellites. New results of the RBSP-Van Allen mission gave new insides about the behavior of electron fluxes (see mentioned papers [Reeves et al., 2016, Ripoll et al., 2017] and multiple other works). It is very difficult to add more for such analysis using the low orbiting Meteor data as ORB electrons are near to isotropic only near ORB polar boundary. Therefore, *we consider that better conditions to observe electrons with >100 keV energy at low latitudes in the Southern hemisphere are connected to the north-south asymmetry of the Earth's magnetic field.*

The estimations of the electron fluxes in the next GGAK-M energy channels (300 and 700 keV) in the outer border of the ORB show that such electron fluxes are not strong enough to be detected by the GGAK-M instrument during quite time (see figure below). Such fluxes can be easily observed only during very disturbed times. Storm-time periods were not analyzed in our study.

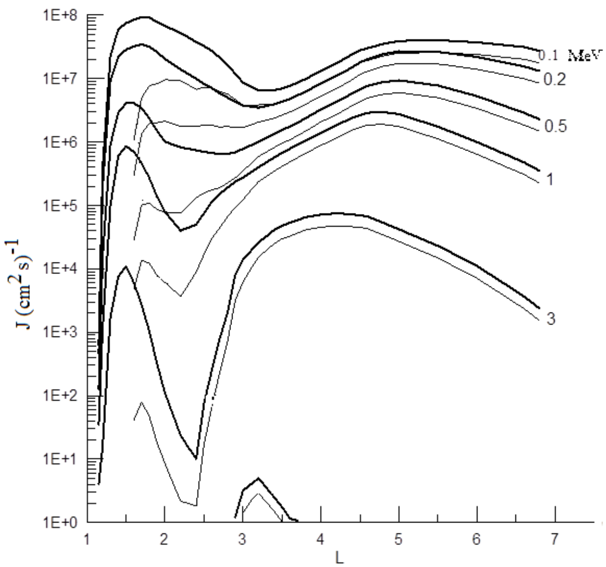

Fig. Radial profiles of the ORB electron fluxes in accordance with quite time AE8 model at the equatorial plane (thick lines) and at B/Beq=3 (thin lines)

Our current work contains the statistics of more than 6200 events of the dropouts to the background level in the electron fluxes with energies more than 100 keV. In the many cases, they were located inside the auroral oval. We did not consider the events of a very strong sharp flux increase at the boundary, because they might be related to the formation of the local particle traps, inside which the energetic electrons can exist during hours [Antonova et al., 2011, J ATMOS SOL-TERR PHY, 73, 1465–1471, doi:10.1016/j.jastp.2010.11.020]. The aforementioned definition is not universal and has its own limitations. In particular, during very quiet geomagnetic conditions the energetic electron fluxes are very low. Therefore, they may reach a defined threshold equatorward from the real ORB boundary. During the analyzed period, the geomagnetic activity was very low. That is why for some events the outer boundary of the ORB was identified to the equator of the equatorial boundary of the auroral oval. We understand that our statistics is sensitive to the energy of threshold, and probably we could have more stable results by elevating its value. Unfortunately, the sensitivity of the high-energy detector onboard the Meteor-M No 1 satellite did not allow us to obtain more accurate results. The new Meteor-

M No2 satellite works at much more disturbed geomagnetic conditions. It allows producing measurements for both quiet and disturbed geomagnetic conditions. We plan to continue these studies and obtain how the position of the trapping boundary depends on the energy.

The study of ORB stability is also far from the subject of our study in presented research. We agree that it is a very interesting problem connected with constantly observed high level of hiss and chorus waves. Presented by Ripoll et al. [2014] results of the long decay periods of electrons in the slot region are rather interesting in this direction. However, such researches are based on the high apogee satellites and deal with highly anisotropic energetic electron fluxes. In our study we work only with data of low orbiting satellite and electron precipitations not so far from the trapping boundary, where auroral fluxes and energetic electron fluxes are varied in every auroral oval crossing, which is in agreement with Reeves et al. [2016] results.

Accelerations for instance will contribute to redistribute the population (e.g. Reeves et al; 2013). All of this energy dependence is left aside by the authors in their study may be because it will be another step, may be because the measurements are not available from the Meteor satellite (with energy integrated sensors), etc. I understand that it is a limitation of the study that is perfectly admissible (because the authors conclusions are already interesting), however, I would like the authors to have a small paragraph on what they think their limitation is (due to energy-integrated measurement) and they comment the fact that their polar boundary is thus an averaged value of energy-dependent polar boundaries, that may vary quite a lot from the dynamic low energy seed population (~100keV) up to the high (ultra-relativistic energies, >1 MeV).

As it was mentioned earlier, in this study we do not analyze the formation of the ORB, which is mainly due to the substorm activity during storms. For instance, we cannot present the comprehensive analysis of energy dependence of the trapping boundary (see above). However comparatively small Larmor radius of energetic electrons - in comparison to the scale of change in the magnetic field - leads to the positioning of all boundaries very close each other in a wide range of energy. The trapping boundary is defined as a boundary which divides the drift trajectories into the trajectories closed inside the magnetosphere and the drift trajectories which intersect the magnetopause. We also know that the maximum in the electron flux of a new radiation belt formed after storm is located at the equatorial boundary of the storm time auroral oval. For example, Reeves et al. [2013] obtained the value L=4 for the 8–9 October 2012 magnetic storm. This storm was later studied by Antonova and Stepanova [2015, EARTH PLANETS SPACE, 67, 148, doi:10.1186/s40623-015-0319-7], who compared the position of the maximum in the electron flux with the position of the maximum in the plasma pressure and the position of the auroral electrojet and found a very good agreement between these positions. During quiet time periods, the auroral oval is mapped to the outer part of the ring current (outer boundary of the oval is located at 10-13 Re according to [Antonova et al., 2017]), therefore we can suggest that the outer boundary of the 1 MeV ORB particles is located inside the auroral oval. However, it is necessary to make additional studies to verify this statement.

We added part of current discussion into the new version of paper.

About the energy-dependence, there is certainly two populations of the electron outer belts which I am asking the authors to distinguish in their discussions: the low energy electron seed, say around 100 keV, from 50 keV maybe up to 200 keV and higher energies, the core of the outer belt. The seed population is extremely dynamic and will penetrate deep (e.g. Zhao et al. 2013; Turner 2015b, 2016). In other words, it is probably harder to identify both inner and polar boundaries for the seed population. Though I believe that is probably what the authors may be observing. A second issue is that the entering of the seeds population in the outer belt does not occur at its boundary, as, for instance, substorm injections often locates around L=4.5 (Turner 2015b). A third point is that the density of the seed population is much higher than the high energy core, so that they probably dominate once one looks after an integrated outer belt boundary.

Indeed, there is a strong difference between so-called seed population and the electrons with highly relativistic energies [Reeves et al., 2016]. However, electrons with energy >100 keV was considered as a part of ORB (see the figure of AE8 model above). We consider the increase of the seed population as a result of not only deep penetration, but also of the acceleration of electrons in the inner magnetosphere due to auroral processes at low latitudes when the auroral oval moves to low latitudes during magnetic storm, which is in agreement with [Turner et al., 2015b] results. Of course, we agree with the statement that the seed population is extremely dynamic, as it was shown in many works including mentioned Zhao et al. [2013], Turner et al. [2015b, 2016]. It is in a very good agreement with the overlapping between the auroral oval and the outer radiation belt, and with the formation of seed population as a result of substorm activity. It is well established that the substorm expansion phase onset starts from the first auroral arc brightening at the equatorial boundary of the auroral oval (see [Akasofu, 1964] and multiple later works). Dispersionless injection boundary is located at L~6-7 in accordance with [Mauk and Meng, 1983, 88(A12), 10011-10024, doi: 10.1029/JA088iA12p10011] and later works. Shift of the auroral oval to low latitudes during storms leads to the shift of the substorm injection boundary. Therefore, the location of the substorm injections at low latitudes is a very natural result, which is in agreement with the partial overlapping of the auroral oval and ORB. Older popular point of view on the formation of the seed population at the outer boundary of ORB is related to the wrong picture of the auroral oval mapping to the plasma sheet. However, this subject now is not discussed in our paper as it cannot be studied using the quiet time Meteor-M No 1 observations.

The aim of our analysis is very simple. We only try to show that the ORB cannot be considered as a region separated from the auroral oval or located at its equatorial boundary. Our statistical study shows that we can see only comparatively small region of the outer part of the ORB where the electron fluxes are nearly isotropic. What is about low latitude injections observed by Turner [2015b], it will be difficult if even possible to study them using low orbiting satellites.

What the polar boundary ends up to carry in terms of energy population is unknown. Its polar boundary surely does not carry all the information of the outer belt energy structure. The core population is expected to be more stable and, as such, to offer a clearer geometry (but less represented in proportion).

On the contrary, when the polar outer belt boundary is created by the simple effect of the magnetopause via magnetopause incursions and the Dst effect (i.e., magnetopause shadowing), the energy-dependence is totally removed and absent, and, as such, the polar boundary of the outer belts is expected to be this time fully energy-independent. That is expected during disturbed times, that constitutes the second part of the authors' study. Such configuration makes the author's current analysis perfectly valid. It would be good to write it. But again, to observe it, would not it be better to have at disposal some energy resolution (rather than none). That last comment could be a good opening for future work.
In other words, if one tries to locate/study the polar boundary of the outer belts is seems to day (with modern technology) more likely to be conclusive if the study is energy-dependent (or at least can be sustained additionally by some energy-dependent measurements), rather than a general global integral for all energies above 100 keV up to 13 MeV, l as the authors do. I don't want to minimize the authors results either, as, as I wrote, has definitely its own merit, but I would like to see such opening to be made.

We completely agree with you. The magnetopause shadowing will produce sharp dropouts of all energies. However, this effect is connected to a large increase in the solar wind dynamic pressure. It is necessary to perform a special research to see such dropout in the low orbiting data especially taking into account that our research was done during comparatively quiet conditions. We hope to continue such researches, as was mentioned, using the Meteor-M No 2 satellite.

Many problems mentioned by you remain to be solved. We think that the auroral processes usually are not considered as a source of energy for ORB formation, giving the preference to the possible contribution of the chorus waves. Analyzing ORB formation, it is necessary to study the behavior of all energetic particles and this requires the correct calculation of the PSD (phase space density). Naturally, we cannot produce such calculations using low orbiting observations. However, what is important, our analysis indirectly shows that it is necessary to be very careful using the models with predefined current systems - as is commonly used for the RBSP data analysis - as such models, as it was shown, lead, for example, to the distortion in the auroral oval mapping.

A last link I would like to see to be made is the link between the interactions of the aurora sub-region with the outer belt seed populations through SAPS (Subauroral polarization Streams, e.g. (Kunduri et al., 2017; Lejosne and Mozer,2017)) potential drop. It has been recently shown that SAPS contribute to the injection (or deeper injections) of the energetic electrons (seed population of the outer belt, upto 200 keV) (Lejosne et al., 2018). This new point has direct implication to the authors' work; 1) it justifies more connecting all aurora associated phenomena and the outer belt dynamics,
2) On the other hand, it explains how fast transport (particularly during disturbed times) will bring more complexity to the outer belt structure, with necessary some implications on its boundaries, 3) it may simply affect the position of their respective boundary, 4) it may open new research angles. Again, it is directly related to the energy dependence of the outer belt, which, as I argue for long enough now here, is a consideration that I would like to see mentioned in this article.

We agree that obtained result on SAPS discovered by Galperin et al. [1973, Kosmicheskie Issledovaniia, 11, 273 - 283] and analyzed in multiple works including latest [Kunduri et al., 2017;

Lejosne and Mozer, 2017; Lejosne et al., 2018] is relevant for the ORB and auroral oval partial overlapping. SAPS are observed just to the equator of the equatorial boundary of the auroral oval and are connected to the Region II field-aligned currents of Iijima and Potemra [1976, JGR, 81, 5971-5979, doi: 10.1029/JA081i034p05971]. Estimations presented by [Lejosne et al., 2018] show that the SAPS electric field can be responsible for a deep penetration of "seed" electrons to a slot region. Unfortunately we cannot clarify the role of the subauroral polarization stream on the position of the ORB outer boundary as we have no observations necessary for the analysis of the electric fields. Inside the SAPS regions such fields are very large. However, it is mainly substorm and, naturally, storm phenomena. That is why we think, that our current statistical results are not affected by SAPS, because they were done during very quiet geomagnetic conditions. Formation of SAPS requires comparatively large geomagnetic activity and, naturally, it will be necessary to analyze the effect selected by Lejosne et al. (2018) when it will be possible to deal with magnetic storms.

We can stress again that in this study we do not analyze magnetic storms. We only try to show that outer part of the outer radiation belt can be located at latitudes of the auroral oval. Actually, we only carefully support very old, but, unfortunately, forgotten point of view of Akasofu [1968].

To conclude, I concretely, ask the authors to account briefly for these aforementioned considerations in their discussions with proper citations (full references given below). For instance, Line 24-30 of the conclusions could be a good place for some of these points as the authors already open their discussion to 'acceleration' and 'transport of seed populations'(but I let the authors decide whether it is in the introduction, discussion, conclusion sections).

We add recommended discussion trying not to go far from the subject and aim of our paper. We included the recommended references, considering that although for instance we cannot see direct connections of the discussed by the Reviewer phenomena with the analysis of the relative position of outer ORB boundary and the equatorial boundary of the auroral oval, these connections might appear in the future. We are sure that the study the auroral oval/ORB relations, which can be responsible not only to the appearance of seed population and its dynamics, would lead to many not expected results.

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Zhao, H., and X. Li (2013), Inward shift of outer radiation belt electrons as a function of Dst index and the influence of the solar wind on electron injections into the slot region, J. Geophys. Res. Space Physics, 118, doi:10.1029/2012JA018179.

Minor corrections:

- P1, Line 10: using the dat

Done

- P1, Line 28: showed that the polar boundary

Done

- P2, Line 27: rephrase "with pitch angle lower than 90°" because every p.a. is below 90°…. Do you mean below and close to 90°?

Yes. We have made the correction.

- P2, Line 28: "due to drift shell splitting (Shabansky effect)". Both are two different things in general. The second can cause the first. Rephrase according to what you want to say. The whole sentence from L25 to L29 is obscure.

done

- -P3, line 8: too strong “has not been properly studied yet”. You could write something like “still requires careful studies” or “careful examination”.
done

- P4, Line 4: make sure the definition “of the polar boundary of ORB, also known as the trapping boundary”, of the trapping boundary is made the first time you mention the “trapping boundary”. (It is not).
done

- P7, Line 7: …oval crossing of the ORB. For…
done

- P10, line 16: “…ring that surrounds..”
done

- P10, line 20: ‘It contains closed
done

- P10, line 21: ‘have drift’
done

- P10, line 23: “of the trapping”
done

- P10, line 25: feel free to include recent references from the Van Allen Probes observations (e.g. reference above)
done

All relevant changes made in the manuscript are shown by blue color in the marked-up manuscript version below.

Relative positions of the polar boundary of the outer electron radiation belt and the equatorial boundary of the auroral oval

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Abstract. Finding the position of the polar boundary of the outer electron radiation belt, relative to the position of the auroral oval, is a long-standing problem. Here we analyze it using the data of the METEOR-M №1 auroral satellite for the period from 11 November 2009 to 27 March 2010. The geomagnetic conditions during the analyzed period were comparatively quiet. METEOR-M №1 has a polar solar-synchronous circular orbit with an altitude of ~832 km, a period of 101.3 min, and an inclination of 98°. We analyze flux observations of auroral electrons with energies between 0.03 and 16 keV, and electrons with energies >100 keV, measured simultaneously by the GGAK-M set of instruments, composed by semiconductors, scintillator detectors, and electrostatic analyzers. We assume that in the absence of geomagnetic storms the polar boundary of the outer radiation belt can be identified as a decrease in the count rate of precipitating energetic electrons to the background level. It was found that this boundary can be located both inside the auroral oval or equatorward of the equatorial boundary of the auroral precipitation. It was also found that for slightly disturbed geomagnetic conditions the polar boundary of the outer radiation belt is almost always located inside the auroral oval. We observe that the difference between the position of the polar boundary of the outer radiation belt and the position of the equatorial boundary of the auroral precipitation depends on the AE and PC indices of geomagnetic activity. The implications of these results in the analysis of the formation of the outer radiation belt are discussed.

1 Introduction

The position of the trapping boundary for energetic electrons in the outer radiation belt (ORB) contains information about the topology of the magnetic field lines of the Earth. For a long time this has been analyzed using data from both low-orbiting and high-apogee satellites (Frank et al., 1964; Frank, 1971; Fritz, 1968, 1970, McDiarmid and Burrows, 1968; Vernov et al., 1969; Imhof et al., 1990, 1991, 1992, 1993; Kanekal et al., 1998 etc.). Using the data of high-apogee satellites, Vernov et al. (1969) showed that the polar boundary of the ORB, also known as the trapping boundary, is located near to ~9R_E in the dayside sector and near to ~7-8 R_E close to midnight. These results were further supported by Imhof et al. (1993) using data from the CRRES and SCATHA satellites, and covering distances from ~6 to ~8.3 R_E (CRRES) and from ~7 to

~8.5 R_E (SCATHA). Results obtained by Fritz (1968, 1970), Imhof et al. (1997), and Yahnin et al. (1997) show that the isotropic boundary of energetic particles (i.e. the boundary where pitch-angle of particles becomes isotropic) is located equatorward of the trapping boundary. It means that the ORB trapping boundary can be clearly identifiable using low orbiting satellites measurements.

A good understanding of the relative positions of the trapping boundary and the equatorial edge of the auroral oval is important for the analysis of the structure of magnetospheric plasma domains and the topology of the geomagnetic field. Comparison of the relative position of the trapping boundary and the auroral oval was statistically done using ground-based auroral observations and satellite observations of the trapping boundary. Akasofu (1968) compared the position of Feldstein's auroral oval with the trapping boundary of the 40 keV electrons obtained by Frank et al. (1964) and statistically showed that the trapping boundary is located inside the auroral oval. However, later Feldstein and Starkov (1970) compared the position of the auroral oval with the results of Alouette-2 observations and concluded that the auroral oval is situated just on the polar border of the trapped radiation region of electrons with energy > 35 keV. Rezhenov et al. (1975) analyzed particle fluxes with energies 0.27, 11, 28 and 63 keV, from the COSMOS-424 satellite, and showed that the trapping boundary is located poleward of the region of low energy electron precipitation. However, this study was done using the data obtained for only 21 orbits, and was not widely known. Feldstein et al. (2014) stressed (p. 120 in their paper), that poleward (high-latitude) boundary of the diffuse auroral belt without any discrete auroral forms "constitutes the equatorward boundary of the auroral oval and at the same time it is the high-latitude boundary of the radiation belt (RB) of electrons with energies from a few tens to hundreds of kiloelectronvolts (STB – stable trapping boundary for radiation belt electrons)".

According to the traditional point of view (see, for example, Paschmann et al. (2002)), the auroral oval is mapped to the plasma sheet. In this case the trapping boundary should be located equatorward or at the equatorial boundary of the auroral oval. However, Antonova et al. (2014a, 2015), and Kirpichev et al. (2016) showed that most part of the auroral oval does not map to the plasma sheet. It is mapped to the plasma ring surrounding the Earth at geocentric distances from ~ 7 R_E to the magnetopause, near noon, and to 10-13 R_E near midnight. They suggested that the plasma in the magnetosphere is in magnetostatic equilibrium, and used the value of plasma pressure as a natural tracer of magnetic field lines, comparing the pressure at low latitudes and at the equatorial plane. Antonova et al. (2017) showed that the outer boundary of this ring in the night sector coincides with the external boundary of the ring current. Results obtained by Antonova et al. (2014a, 2015, 2017), and Kirpichev et al. (2016) showed that the auroral oval is mapped to the region of quasitrapping, where drift trajectories of energetic electrons with pitch-angles smaller than near to 90° surround the Earth (Delcourt and Sauvaud, 1999; Öztürk and Wolf, 2007; Ukhorskiy et al., 2011; Antonova et al., 2011a) due to drift shell splitting effect (which is ordinarily named as Shabansky effect). Such mapping suggests that the trapping boundary should be located poleward of the equatorial boundary of the auroral oval.

Therefore, it is very important to establish the true location of the trapping boundary with respect to the equatorial auroral oval boundary. This can be done using simultaneous observations of both auroral electron precipitation and fluxes of energetic electrons. It is well known that the location of the auroral oval and the location of the trapping boundary are strongly affected by geomagnetic activity. Therefore, it is necessary to compare these relative locations using simultaneous measurements of the auroral oval and trapping boundary on the same satellite. However, there are some difficulties related to the detection of the trapping boundaries during the periods of low geomagnetic activity (for example during the solar minimum). In these cases, the level of electron fluxes inside the ORB can be rather low, close to the limit of sensitivity of the instrument. Thus, the detected trapping boundary can be located closer equatorward with respect to the true trapping boundary.

Despite the significant amount of particle measurements carried out by low-orbiting satellites, the relative location of the trapping boundary and the equatorial boundary of the auroral oval, and how they could be affected by geomagnetic activity, still requires careful studies. In this work, we use data of the satellite METEOR-M №1 to establish the location of the trapping boundary and of the auroral oval for different levels of geomagnetic activity, which were quantified using the AE and PC geomagnetic indices. The paper is organized as follows. First, we describe the METEOR-M №1 satellite instrumentation and the data analysis, including important caveats. Then we obtain the position of the trapping boundary of electrons with energies >100 keV relative to the equatorial boundary of the auroral oval, and how it varies for small and large values of the AE and PC indices of geomagnetic activity. At the end, we shall discuss the role that our results might play on the determination of features of the high-latitude magnetospheric topology.

2 Instrumentation and data analysis

We used the data from the METEOR-M №1 satellite launched 17 September 2009 into a polar solar-synchronous circular orbit with an altitude of ~830 km, a period of ~100 min, and an inclination of 98°. We used the data of the GGAK-M set of instruments, composed by semiconductor and scintillator detectors, and electrostatic analyzers. In particular, it measured energetic electrons with energies from 0.1 to 13 MeV, and low energy electrons with energies from 0.032 to 16.64 keV (see more details and available data in http://smdc.sinp.msu.ru/index.py?nav=meteor_m1).

For automatic detection of the polar boundary of the ORB and the equatorial boundary of the auroral oval we compared the corresponding fluxes with a background reference flux, calculated for each orbit. For energetic particles we calculated the average flux of electrons with energies >100 keV in the polar cap and its standard deviation. We assumed that the measured flux can be classified as ORB electron flux if the difference between this flux and the background flux was greater than five standard deviations during the continuous time interval of at least 1 minute duration (the separate single points spikes are not taken into account). The nearest poleward point that satisfies the described criterion is selected as the polar boundary of the ORB. These selection criteria show stable results of the ORB detection but as a rule they define the boundary at the end of the decline of electron intensity from ORB maximum to the background level. This means that electron fluxes lower than the established criteria, and belonging to the ORB, could be missed. This is why it might shift slightly the obtained boundary equatorward with respect to the true boundary especially in the case of low intensity ORB crossing (see the introduction). This means that we could underestimate the number of events for which the polar boundary of the ORB is observed inside the auroral oval. Such underestimation changes slightly the results of the statistical analysis. However, it cannot change the answer to the main question: whether the trapping boundary is located inside the oval or coincides with its equatorial boundary.

The automatic detection of the polar boundary of ORB, identified as the trapping boundary, might be affected by the sharp local increases in the energetic electron fluxes sometimes observed at the trapping boundary (see Imhof et al. (1990, 1991, 1992, 1993)) or just poleward of it. Such fluxes are usually much smaller than the maximum fluxes of the ORB precipitating electrons. Nevertheless, they can be observed during a few hours at the same location in a few consecutive polar satellite orbits (Myagkova et al., 2010; Antonova et al., 2011b; Riazantseva et al., 2012), and alter the automatic detection of the boundary. It was one of the reasons to do a visual inspection of all events.

To calculate the position of the auroral oval boundary, we use the value of the total energy flux. We produce the spectra approximation from 0.032 till 16.64 keV with energy step dε=0.01 keV. Energy flux was calculated as the integral characteristic of low energy electron spectrum $Flux_{\varepsilon} = 2\pi \int (j(\varepsilon) \cdot \varepsilon \, d\varepsilon)$ (j(ε) is the flux for current value of energy ε). We first calculated the average value and standard deviation of the electron energy flux measured at L<3 Re, where L is the McIlwain parameter. In the next step we considered the fluxes that exceed the background flux seven standard deviations. If the obtained boundary was located at L>3 Re, we repeated this procedure but calculating the average flux and its standard deviation up to the boundary, determined in the first step. Based on the Vorobjev et al. (2013) definition of the auroral oval, we also imposed additional criterion to the value of the total energy electron flux: it should be greater than 0.2 erg/cm^{2}s. The results obtained were also confirmed by a visual inspection.

We used the AE index (Davis and Sugiura, 1966) that represents the dynamics of the auroral electrojet, to identify the intervals of substorm activity. We also used the Polar Cap (PC) index (Troshichev and Andrezen, 1985; Troshichev and Janzhura, 2012), which was created as a proxy of dawn-dusk electric field in the polar cap and Region 1 currents of Iijima and Potemra (1976) intensity. We took for the analysis the one minute values of the AE and PC indices when the spacecraft was at the equatorial boundary of the auroral oval. Taking into account that there are two PC indices, obtained for the northern (PCN) and southern (PCS) hemispheres, we used the corresponding PCN (PCS) indices for northern (southern) crossings of the auroral oval.

Figure 1 shows an example of two crossings of the auroral oval in the morning and evening MLT sectors on 01 February 2010, when the trapping boundary was located inside the auroral oval. The top panel shows the spectrogram of low energy electrons, the bottom panel shows total energy flux, calculated from the electron spectra presented on the top (red solid line) and counts of electrons with energy ≥ 100 KeV (green solid line). Dashed red lines in both panels indicate the position of the equatorial boundaries of the auroral oval and dashed green lines show the position of the polar boundaries of ORB. It is clearly seen that the curves of total energy flux and counts of electrons with energy ≥ 100 KeV show the position of the trapping boundary poleward of the equatorial boundary of the auroral oval.

According to the omniweb database (http://omniweb.gsfc.nasa.gov/), the solar wind number density (Nsw) and velocity (Vsw), and of three components of the interplanetary magnetic field (IMF) for both equatorial borders were very common: Bx≈2 nT, By≈-4 nT, Bz≈-1 nT, Nsw≈6 cm^{-3}, and Vsw≈450 km/s. This event took place in the absence of geomagnetic storms (Dst≈-7 nT), and during moderate auroral activity (150 nT<AE<300 nT, and AL>-300 nT). The values of PC index were also moderate (PCS<3) (see http://pcindex.org). As it can be seen, for this event the trapping boundary of energetic electrons, shown by green dashed lines, is located inside the auroral oval. The differences between the latitudes of the equatorial boundary of the oval and the trapping boundary, ΔLat are equal to -5.8° for the dawn and -1.7° for the dusk boundaries.

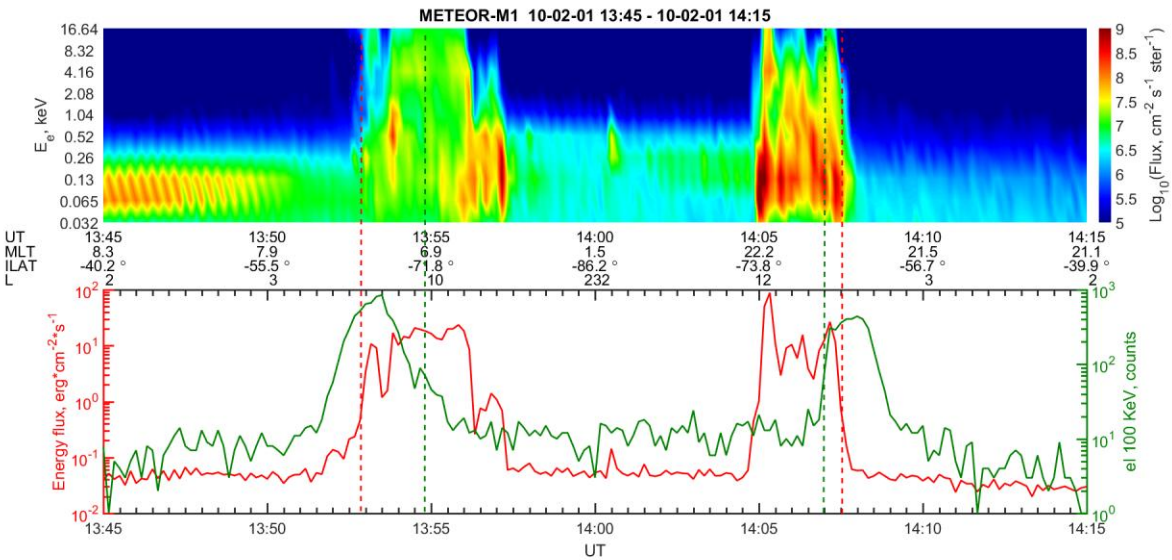

Figure 1: An example of the location of the polar boundary of ORB inside the auroral oval at AE>150 nT. Top panel -spectrogram of low energy electrons, bottom panel: red solid line - total energy flux, calculated from the electron spectra presented on the top; green solid line - counts of electrons with energy ≥ 100 KeV; dashed red lines mark the position of the equatorial boundaries of the auroral oval; dashed green lines - the position of the polar boundaries of ORB.

Figure 2 shows an event of the trapping boundary located outside the auroral oval observed on 17 January 2010. The satellite crossed twice the auroral oval during very quiet geomagnetic conditions (Bx≈2 nT, By≈-1 nT, Bz≈2.5 nT, Nsw≈6 cm^{-3}, Vsw≈350 km/s, Dst≈-2 nT, AE≈15 nT, AL≈-15 nT, PCN<1). The observed difference was comparatively small: Δ Lat =1° for the dawn and 3.3° for the dusk boundaries.

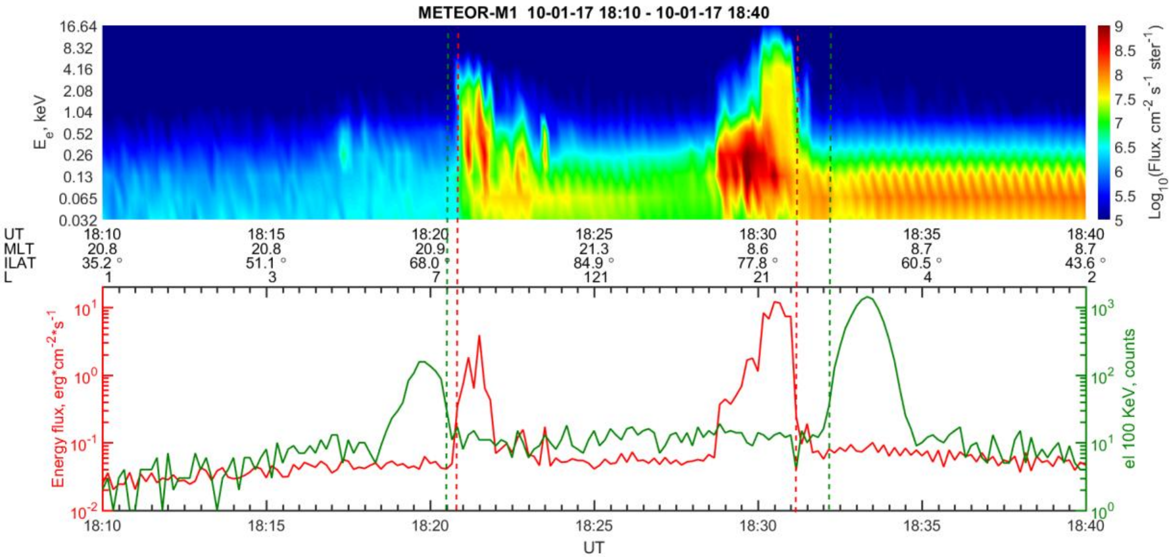

Figure 2: An example of observation of the polar boundary of ORB outside the auroral oval at AE<150 nT. The notations are the same as in Fig.1

Comparison of events shown in Fig. 1 and 2 could bring to a conclusion that the relative location of the trapping boundary and the equatorial boundary of the auroral oval might be affected by the shift of the oval to higher latitudes with the decrease of the geomagnetic activity. However, there are many other events observed for low activity for which the trapping boundary was observed inside the oval. One of examples of such kind of events is shown in Fig. 3.

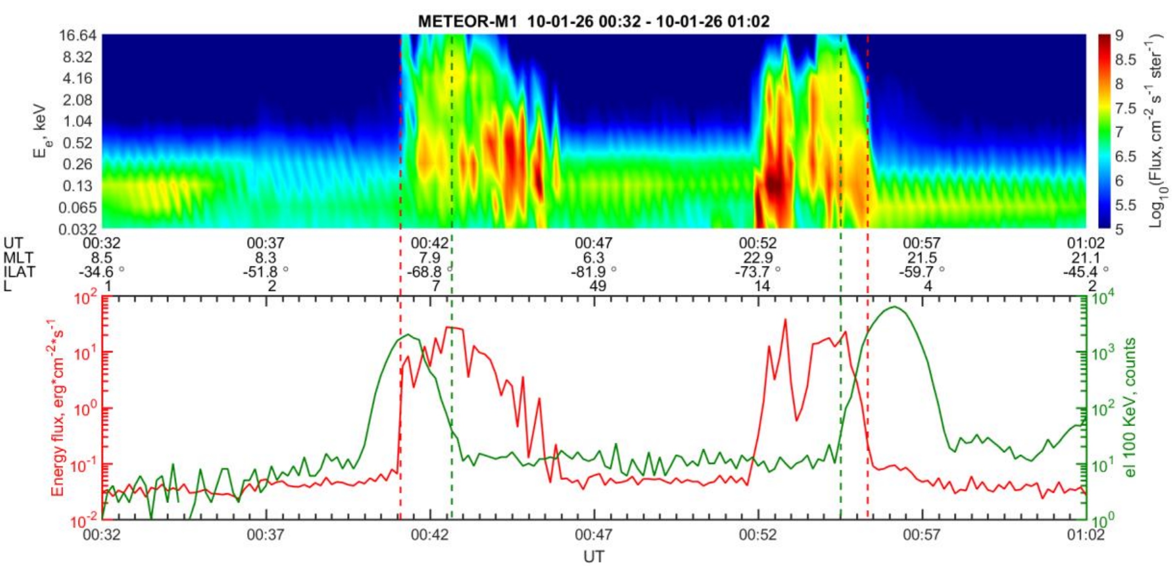

Figure 3: An example of observation of polar boundary of ORB inside the auroral oval at AE<150 nT. The notations are the same as in Fig.1

It took place on 26 January 2010 during quiet geomagnetic conditions (IMF Bx≈-2.2 nT, By≈-4.0 nT, Bz≈-1.5 nT, Nsw≈3.5 cm^{-3}, Vsw≈370 km/s, Dst≈-17 nT, AE≈50 nT AL≈-30 nT, and PCS<1). For this event, Δ Lat =-5.1° for the dawn and -2.2° for the dusk sectors.

Existence of different types of events requires making a statistical analysis to clarify how the geomagnetic conditions could affect the relative location of both boundaries.

3 Statistical analysis

We analyzed the data from METEOR-M №1, obtained for more than 6200 auroral oval and the outer boundary of the ORB crossings. For each crossing, we determined the difference between the geomagnetic latitudes of the equatorial boundary of the auroral oval and of the trapping boundary, Δ Lat. The negative difference Δ Lat <0 means that the trapping boundary is located inside the auroral oval while the positive difference Δ Lat >0 indicates that the trapping boundary is located equatorward of the auroral oval. The METEOR-M №1 satellite has a sun-synchronous orbit. That is why we obtained Δ Lat only for a limited range of MLTs.

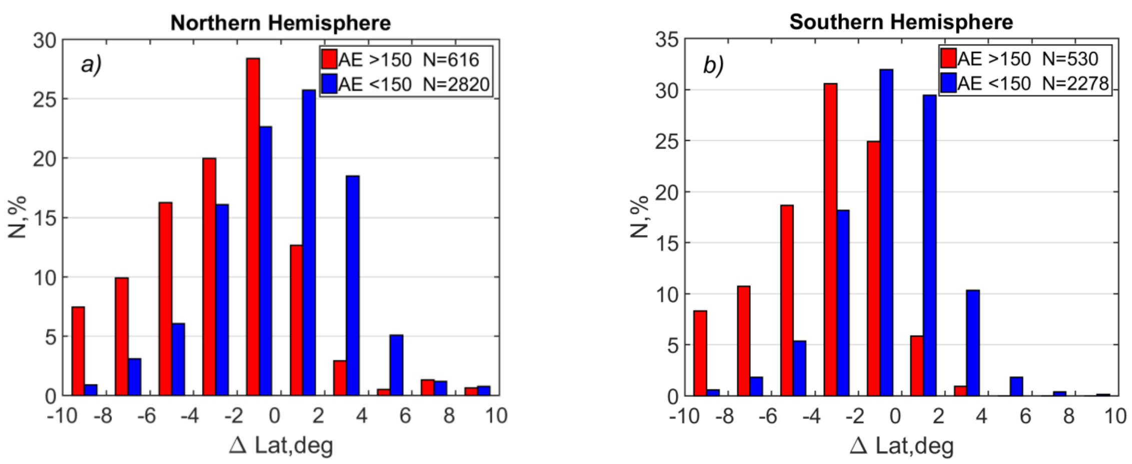

Figure 4: The distribution of Δ Lat for AE>150 nT (red bins) and <150 nT (blue bins) for northern (a) and southern (b) hemispheres. N show the number of events under described criteria.

To analyze how these differences could be affected by geomagnetic activity, we divided all data into two data sets according to the AE or PC indices. Figure 4 shows the distribution of the latitude differences Δ Lat for AE>150 nT and AE <150 nT for the northern (a) and southern (b) hemispheres. As it can be seen, the number of events for which the trapping boundary is observed inside the auroral oval increases significantly with the increase of geomagnetic activity, quantified through the AE index. For AE>150 nT the trapping boundary is located inside the auroral oval for the majority of events for both hemispheres, while for AE<150 the trend is not so clear - the number of events where the trapping boundary is located inside and outside of the auroral oval is nearly the same. However, for both sets there are a comparatively large number of events, for which this difference is comparatively small.

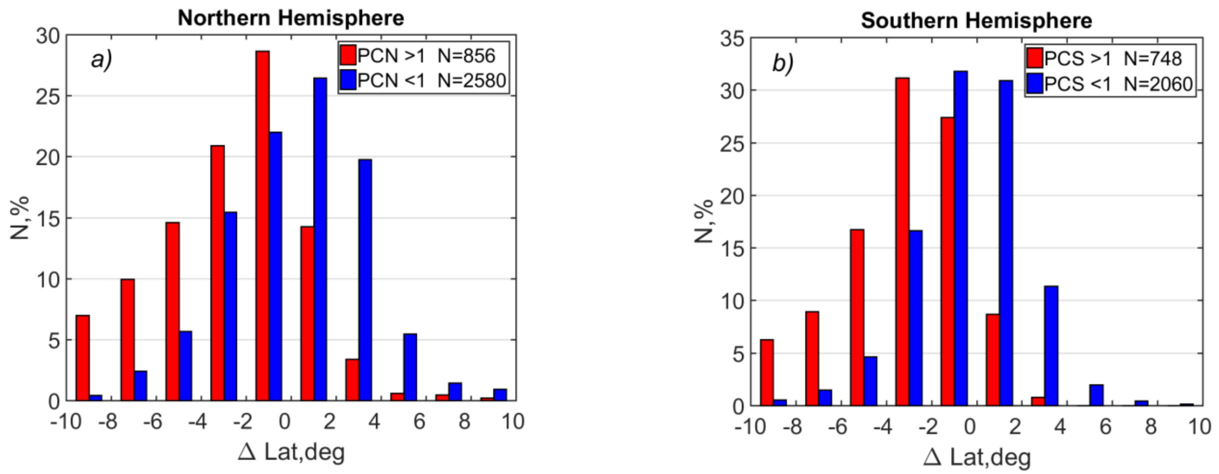

Figure 5: The distribution of Δ Lat for PC>1 (red bins) and <1 (blue bins) for northern (a) and southern (b) hemispheres. N show the number of events under described criteria.

Figure 5 shows the distribution of the latitude differences Δ Lat for PC>1 and <1 and for the northern (a) and southern (b) hemispheres, respectively. Comparing Fig. 4 and 5, we can see that both distributions are very similar, which can be explained by high correlation between the AE and PC indices obtained by Vennerstrøm et al. (1991). This correlation is related to the formation of ionospheric current systems as a result of the magnetosphere-ionosphere interactions, and the dominant role of the Region 1 currents of Iijima and Potemra (1976) in the formation of the PC index (Troshichev and Janzhura, 2012). However, the obtained similarity in the behavior of the boundaries, using the AE and PC indices as separate measures of geomagnetic activity, was not evident at the beginning of this study. This supports the picture obtained by Akasofu (1968) in which the trapping boundary is located inside the auroral oval. We underline that the described effect can be clearly seen only in case of simultaneous measurements of plasma and energetic electrons on board of the same satellite, which allow to observe the trapping boundary inside the auroral oval directly during the local measurements. The statistical comparison of boundaries masks this effect, because the scattering of the position of the discussed boundaries in different crossings can be rather large (the standard deviation in the statistical position of the boundaries ≈ ±2° for the trapping boundaries and ≈ ±3° for the equatorial boundaries of the auroral oval) whereas the main part of ΔLat distributions in Fig.4 and 5 show the difference between boundaries within the limits ±2° in case of low geomagnetic activity. The observed scattering in positions of the boundaries are in agreement with early established scattering of the auroral oval boundaries (see Vorobjev et al. (2013) and references therein) and the outer ORB boundary (Kanekal et al., 1998, Kalegaev et al., 2018).

The analysis of the shifts of the studied boundaries with the increase of geomagnetic activity requires special attention and it is far from the main subject of our research. Figure 6 shows the L (McIlwain parameter) – distribution of both boundaries for AE<150 nT and AE>150 nT in both hemispheres. It is possible to see the real shift of the equatorial boundary of the auroral oval equatorward with the increase of AE, which is well known due to multiple auroral oval observations. At the same time the position of the trapping boundary practically does not change with the increase of AE. This result is in agreement with Kanecal et al. [1998], in that, in comparison with plasma boundaries, the energetic particle boundaries show a lower degree of correlation with solar wind Bz, VBz, and Kp index of geomagnetic activity.

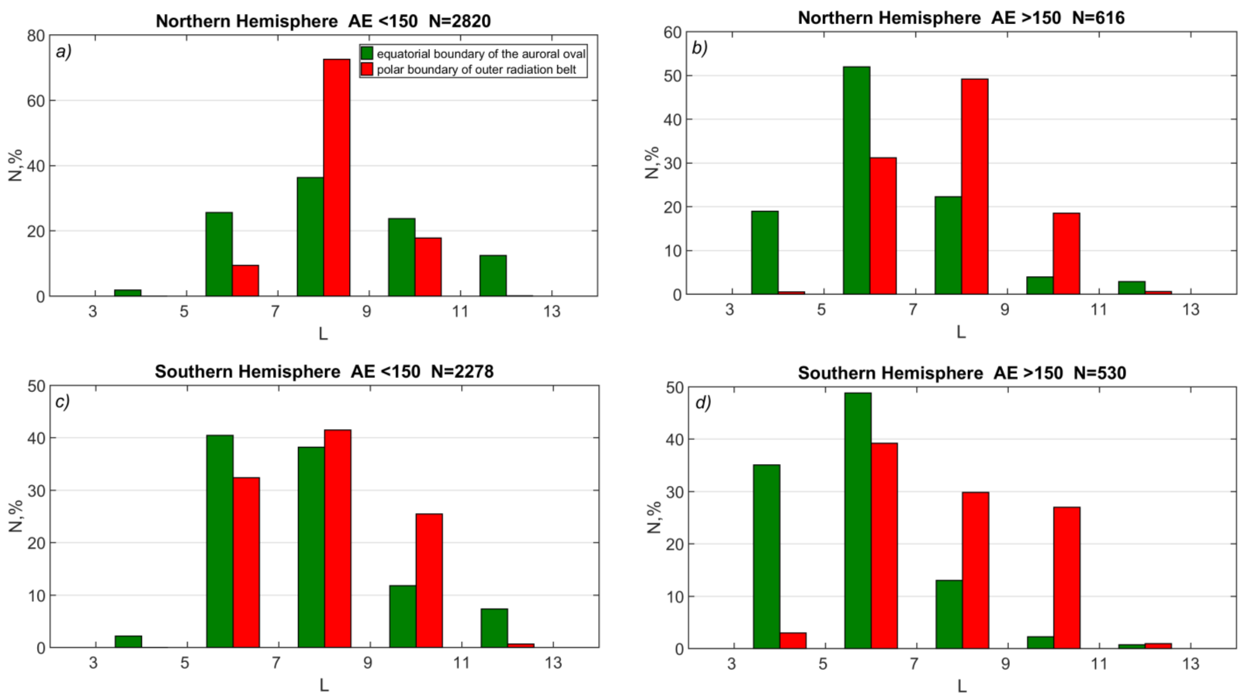

Figure 6: The distributions of the position of the equatorial boundary of the auroral oval (green bins) and the polar ORB boundary (red bins) from the L (where L is the McIlwain parameter) for northern (a,b) and southern (c,d) hemispheres for AE <150 nT (a,c) and AE>150 nT (b,d).

4 Discussion and conclusions

We analyzed the relative position of the trapping boundary and the equatorial boundary of the auroral oval using simultaneous measurements of the energetic electrons with energy >100 keV and the auroral electrons made at the same METEOR-M №1 satellite. Previous comparisons of the relative position of these boundaries were made mostly statistically using data from different satellites. Our analysis shows that the differences in the positions of both boundaries are typically smaller than the statistical scattering in the position of each boundary. This fact explains why previous statistical studies led to different conclusions, and why the use of statistical results about the location of each boundary cannot answer the question about the relative position of the trapping boundary and the equatorial boundary of the auroral oval.

Our study shows the trapping boundary is often located inside the auroral oval. The number of such events would be enhanced if instruments of better sensitivity were used. This is because the trapping boundary is defined as the boundary where particle fluxes become lower than a threshold determined by the sensitivity of a detector in case of low level of electron flux inside the ORB, so an increase in the sensitivity would move the detected trapping boundary poleward, i.e. deeper inside the auroral oval. The analysis of the latitudinal difference in the position of both boundaries for AE more or less than 150 nT, and for PC more or less than 1 shows that the number of events when the trapping boundary is observed inside the auroral oval significantly increases with both AE and PC indices.

The location of the trapping boundary inside the auroral oval agrees with latest results on the auroral oval mapping discussed by Antonova et al. (2017). They argue that the auroral oval has a form of a comparatively thick ring for all MLTs. Mapping of the plasma sheet to the ionospheric altitudes cannot produce the structure with non-zero thickness near noon. Therefore, it seems natural to map the auroral oval into the plasma ring that surrounds the Earth, as selected by Antonova et al. (2013, 2014b), and filled with plasma similar to the plasma in the plasma sheet. Results of Antonova et al. (2014a, 2015) and Kirpichev et al. (2016) also support such conclusion and locate the quiet time equatorial boundary of the auroral oval at R~7 R_E near midnight and polar boundary at R~10-13 R_E. It is also important to remember that starting from Vernov et al. (1969) this magnetospheric region is classified as the region of quasitrapping for energetic particles. It contains locked inside the magnetosphere drift trajectories, and only particles with near to 90° pitch-angles have drift trajectories crossing the magnetopause. The drift trajectories of particles with other pitch angles are locked inside the magnetosphere. Therefore, the registration of the trapping boundary of energetic electrons with nearly zero pitch angles inside the auroral oval seems quite natural.

The observation of the trapping boundary of energetic electrons inside the oval can also be important for the solution of the problem of acceleration of electrons in the ORB, taking into account that the injection of seed population of relativistic electrons during magnetic storms takes place at the equatorial boundary of the auroral oval (see the results and discussion in (Antonova and Stepanova, 2015)). Electrons of such seed population must be trapped inside the magnetosphere and further accelerated to relativistic energies during the recovery phase of storm, forming a new ORB. Our current studies were done for comparatively quiet geomagnetic conditions. It also point out the necessity to keep studying the position of the ORB boundaries taking into account an overlapping of the part of the auroral oval and the ORB, using a more sophisticated instrument for the measurement of energetic electrons, and to extend this study to the geomagnetic storm time intervals. For our study we used integrated fluxes of the precipitating electrons with the energy > 100 keV. Hence, our results provide the information about an averaged value of polar boundaries, which might vary significantly from the dynamic low energy seed population (~100 keV) up to the high (ultra-relativistic energies >1 MeV), taking into account that the seed electron acceleration to higher energies, and the radial diffusion contributes to the redistribution of the electron population (see

(Reeves et al; 2013; Zhao et al. 2013; Turner 2015a,b, 2016). It is necessary to add, that the recent results including the observations of the Van Allen Probes has led to significant advances in the study of the dynamics of the ORB. For example, (Ripoll et al. 2014) showed the existence of a rather stable core of the ORB. The energy dependence of the inner boundary of the ORB was carefully analyzed by (Reeves et al. 2016; Ripoll et al. JGR 2017), and injection of seed population at low latitudes was studied by (Turner et al., 2015b). Recent studies Makarevich et al. (2009), Kunduri et al. (2017), Lejosne and Mozer (2017) are of a special interest, showing a strong increase of transverse electric fields in subauroral polarization streams (SAPS), which according to Lejosne et al. (2018) can modify the picture of particle injection in the slot region. However, it will be interesting to continue researches of the outer radiation belt considering the results obtained in our paper.

In summary, we can conclude that the trapping boundary of electrons with energy >100 KeV, which coincides with the polar boundary of the ORB, is often located inside the auroral oval. This applies almost always to high geomagnetic activity times and also, though less often, to low geomagnetic activity times. All this that might help to re-analyse the relation between the dynamics of radiation belts and auroral phenomena.

Acknowledgments

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